

NECESSARY CONDITIONS FOR SHORT GAMMA-RAY BURST PRODUCTION IN BINARY NEUTRON STAR MERGERS

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ABSTRACT

The central engine of short gamma-ray bursts (sGRBs) is hidden from direct view, operating at a scale much smaller than that probed by the emitted radiation. Thus we must infer its origin not only with respect to the formation of the *trigger* - the actual astrophysical configuration that is capable of powering a sGRB - but also from the consequences that follow from the various evolutionary pathways that may be involved in producing it. Considering binary neutron star mergers we critically evaluate, analytically and through numerical simulations, whether the neutrino-driven wind produced by the newly formed hyper-massive neutron star can allow the collimated relativistic outflow that follows its collapse to actually produce a sGRB or not. Upon comparison with the observed sGRB duration distribution, we find that collapse cannot be significantly delayed (≤ 100 ms) before the outflow is choked, thus limiting the possibility that long-lived hyper-massive remnants can account for these events. In the case of successful breakthrough of the jet through the neutrino-driven wind, the energy stored in the cocoon could contribute to the precursor and extended emission observed in sGRBs.

Subject headings: hydrodynamics — relativistic processes — gamma-ray burst: general — stars: winds, outflows — stars: neutron

1. INTRODUCTION

The most popular model for short gamma-ray bursts (sGRBs) invokes the coalescence of binary neutron stars and the subsequent production of a beamed, relativistic outflow (Eichler et al. 1989; Paczynski 1991; Narayan et al. 1992; Meszaros & Rees 1992). The launching of a relativistic jet requires material with sufficient free energy to escape the gravitational field of the central object as well as a mechanism for imparting some directionality to the outflow (Mochkovitch et al. 1993; Rosswog & Ramirez-Ruiz 2003; Aloy et al. 2005; Rezzolla et al. 2011; Palenzuela et al. 2013). A potential death trap for such relativistic outflows is the amount of entrained baryonic mass from the surrounding environment (see e.g. Lee & Ramirez-Ruiz 2007, and references therein). In neutron star binaries the elevated post-merger neutrino fluxes are capable of ablating matter from the surface of the remnant at a rate

$$\dot{M}_w \approx 5 \times 10^{-4} \left(\frac{L_\nu}{10^{52} \text{ erg/s}} \right)^{5/3} M_\odot/\text{s} \quad (1)$$

(Qian & Woosley 1996; Rosswog & Ramirez-Ruiz 2002; Dessart et al. 2009). Thus the rest mass flux arising from the neutrino-driven wind bounds the bulk Lorentz factor of the jet to

$$\Gamma_\nu \approx 10 \left(\frac{L_{\text{jet}}}{10^{52} \text{ erg/s}} \right) \left(\frac{\dot{M}_w}{5 \times 10^{-4} M_\odot/\text{s}} \right)^{-1} \quad (2)$$

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and hence the successful launch of a highly relativistic jet might have to wait until the collapse of the merger remnant and the ensuing formation of the black hole plus debris disk system.

The fate of the post-merger, hyper-massive neutron star is, however, uncertain, and is contingent on the mass limit for support of a hot, differentially rotating configuration (e.g. Baumgarte et al. 2000; Duez et al. 2006; Giacomazzo & Perna 2013; Hotokezaka et al. 2013a). The threshold for collapse can be calculated roughly as $M_{\text{thres}} = 1.35 M_{\text{cold}}$ (Shibata & Taniguchi 2006), where M_{cold} is the corresponding value for a cold, non-rotating configuration. In agreement with the mass determination in PSR J0348+0432 ($M_{\text{cold}} \gtrsim 2M_\odot$; Demorest et al. 2010), a total mass greater than $\approx 2.7M_\odot$ is required for prompt collapse to a black hole. When $M_{\text{cold}} < M < M_{\text{thres}}$, various mechanisms could act to dissipate and/or transport energy and angular momentum, possibly inducing collapse after a delay which could range from tens of milliseconds to a few seconds (for a recent review see Faber & Rasio 2012). During this period, a baryon loaded wind is continuously ejected for a time t_w , which precedes jet formation (Lehner et al. 2012). As a result, a dense wind remains to hamper the advance of the jet, whose injection lifetime, t_j , is determined by the viscous time scale of the neutrino-cooled disk (Lee et al. 2004, 2005a; Setiawan et al. 2004; Metzger et al. 2008a; Lee et al. 2009).

In this *Letter*, we study with the use of hydrodynamical simulations how the expansion of the relativistic jet is modified by the previously ejected wind and investigate the conditions necessary for successful sGRB production in binary neutron star mergers. There are three sections. Section 2 gives an account of the properties that determine the advancement of the jet in the wind and its possible successful emergence. Section 3 describes the results of the numerical calculations. Finally, Section 4 gives a compendium of the types of observational sig-

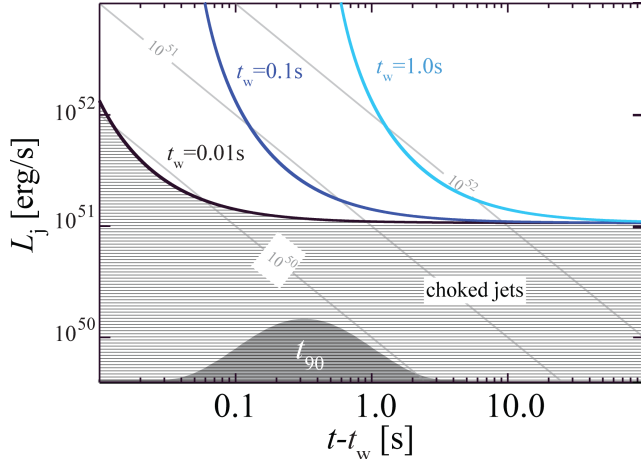


FIG. 1.— This plot illustrates how the jet expansion would be affected by the properties of the wind which it propagates. The axes (logarithmic) are L_j versus $t - t_w$, where $t - t_w = 0$ denotes the time when the wind injection terminates and the jet starts its expansion. The lines represent the time it takes for the jet to break free ($t_{j,b}$) from a wind with $\dot{M}_w = 10^{-3} M_\odot \text{ s}^{-1}$ and $\beta_w = 0.3$ for $t_w = 0.01, 0.1, 1$ s. Lines of constant (isotropic equivalent) jet energy are plotted as grey solid lines (we have assumed $h_j = 1$). When $t_w > 0.1$ s, jet injection times in excess of sGRB durations, illustrated here by the t_{90} distribution (Nakar 2007; Gehrels, Ramirez-Ruiz & Fox 2009), are required in order to breakout from the wind.

natures expected for jets propagating through neutrino-driven winds of different mass loading and durations together with a model proposal for generating sGRBs with precursor and extended emission.

2. UNDERSTANDING JET PROPAGATION AND CONFINEMENT

The properties of the neutrino-driven wind have an important effect on a jet propagating through it. If the isotropic equivalent power in the jet, L_j , is roughly conserved and stationary, then we balance momentum fluxes at the working surface to obtain (Matzner 2003; Bromberg et al. 2011)

$$\beta_h = \frac{\beta_j}{1 + \tilde{L}^{-1/2}}, \quad (3)$$

where β_h and β_j are the head and shock velocities respectively, and both the shocked jet material and the shocked wind material advance with a jet head Lorentz factor $\Gamma_h \ll \Gamma_j$ (Ramirez-Ruiz et al. 2002). Here

$$\tilde{L} = \frac{\rho_j}{\rho_w} h_j \Gamma_j^2, \quad (4)$$

where ρ_w denotes the density of the wind material and h_j the specific enthalpy of the jet.

In a wind medium such that $\rho_w = \dot{M}_w / (4\pi\beta_w r^2 c)$, the jet head's velocity is steady, assuming the opening angle of the jet remains constant. Thus, the breakout time for a steady jet propagating through a wind with a velocity β_w , injected during a time t_w is given by

$$t_b = t_w \frac{\beta_h}{\beta_h - \beta_w}, \quad (5)$$

where $t = 0$ denotes the wind injection time. As the jet makes its way out and its rate of advance is slowed down, most of the energy output during that period is deposited into a cocoon surrounding it (Ramirez-Ruiz et

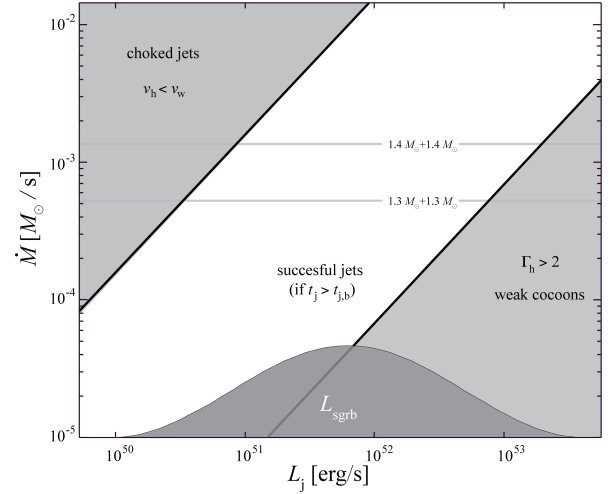


FIG. 2.— Characteristic behavior of relativistic jets expanding within a neutrino-driven wind. L_j/\dot{M}_w controls the rate of advance of the head of the jet while t_w/t_j determines whether or not the jet would be able to break free of the neutrino driven wind. For comparison, the distribution of isotropic equivalent luminosities for observed sGRB is plotted (Berger 2013; Margutti et al. 2013) together with an estimate of \dot{M}_w for a $1.4 M_\odot + 1.4 M_\odot$ neutron star merger (Dessart et al. 2009). The mass loss rate expected for a $1.3 M_\odot + 1.3 M_\odot$ merger is calculated here using the relationship between L_ν and post-merger remnant mass derived in Rosswog & Ramirez-Ruiz (2003). Similar values for \dot{M}_w are estimated using magnetically-driven wind models (Siegel et al. 2014).

al. 2002). The jet would be expected to break free of the dense wind, and in principle lead to a successful sGRB, provided the central engine feeding time t_j exceeds

$$t_{j,b} = t_b - t_w = t_w \frac{\beta_w}{\beta_h - \beta_w}. \quad (6)$$

Fig. 1 shows the luminosity required for a jet to breakout from a wind medium with $\dot{M}_w = 10^{-3} M_\odot \text{ s}^{-1}$ and $\beta_w = 0.3$. Three cases are depicted for $t_w = 0.01, 0.1, 1$ s. The most favorable region for shocks producing highly variable γ -ray light curves is above the edge of the wind, while the radiation emitted by shocks occurring below it would be drastically absorbed as the optical depth across the wind is enormous. If collapse to a black hole is significantly delayed (i.e. $t_w > 0.1$ s), the majority of jets, with the exception of some very luminous ones, will not breakout during the typical duration of a sGRB (t_{90}). If, on the other hand, collapse occurs more promptly (i.e. $t_w \leq 0.1$ s), the successful break-through of the jet would lead to a detectable sGRB followed by a standard afterglow. It is not necessary for the head of the jet to move at a high bulk Lorentz factor as it transverses the dense wind. As long as the emergent outflow has a high enthalpy per baryon, it will expand and achieve its high terminal speed some distance from the edge of the wind.

Irrespective of t_j/t_w , a choked jet will invariably result if $\beta_h/\beta_w < 1$. This condition can be rewritten as

$$L_j \lesssim 1.1 \times 10^{51} \left(\frac{\dot{M}_w}{10^{-3} M_\odot/\text{s}} \right) \text{ erg/s}. \quad (7)$$

By contrast, relativistic expansion of the jet head within the wind medium would be guaranteed if $\tilde{L} \gg 1$, which

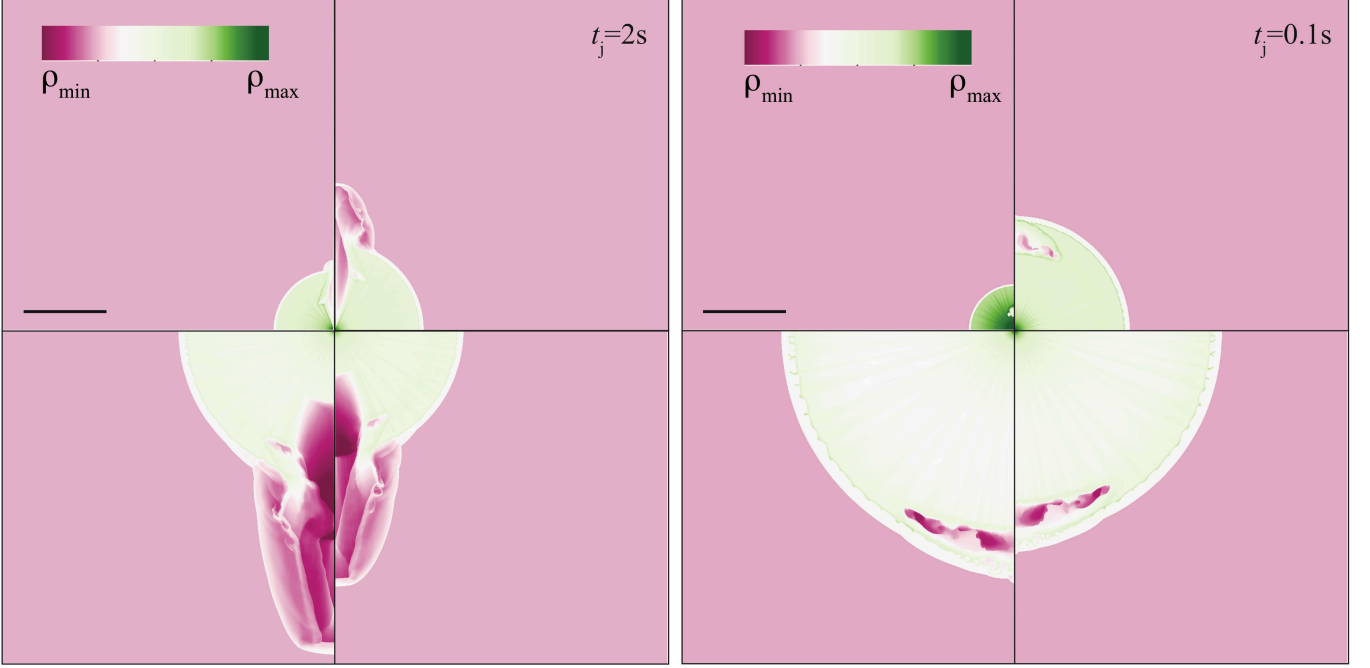


FIG. 3.— The evolution of a sGRB jet in a steady neutrino-driven wind with $\dot{M}_w = 10^{-3} M_\odot \text{ s}^{-1}$ and $\beta_w = 1/3$. The jet is characterized by $L_j = 10^{51} \text{ erg s}^{-1}$, $\theta_j = 10^\circ$ and $\Gamma_j = 10$. Two illustrative cases are shown for $t_{j,b} < t_j = 2 \text{ s}$ (left panel) and $t_{j,b} > t_j = 0.1 \text{ s}$ (right panel). Shown are logarithmic density contours $[\rho_{\min}, \rho_{\max}] = [2 \times 10^{-5}, 7.0]$ in g cm^{-3} together with a $3 \times 10^{10} \text{ cm}$ scale bar. Each snapshot has been rotated by $\pi/2$, where $t = 2, 3, 4.5, 5.5 \text{ s}$ (left panel) and $t = 1.5, 4, 7, 8.5 \text{ s}$ (right panel). Calculations were done in two-dimensional cylindrical coordinates using an adaptive grid of physical size $l_r = l_z = 1.2 \times 10^{11} \text{ cm}$, with 300×300 cells on the coarsest grid and 7 levels of refinement, which corresponds to a maximum resolution of $6.25 \times 10^6 \text{ cm}$.

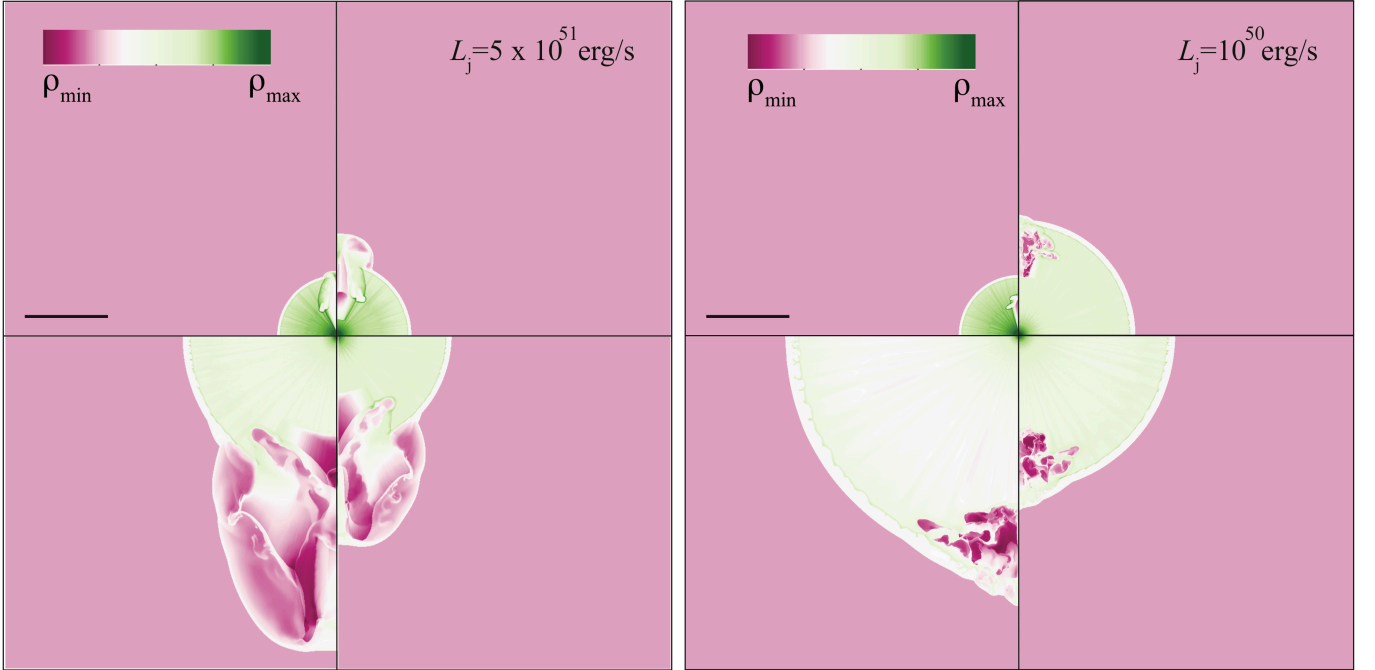


FIG. 4.— The evolution of sGRB jets of varying power interacting with a wind with $\dot{M}_w = 10^{-3} M_\odot \text{ s}^{-1}$ and $\beta_w = 1/3$. The numerical setup is identical to that used in Fig. 3. The jet is characterized by $t_j = 1 \text{ s}$, $\theta_j = 10^\circ$ and $\Gamma_j = 10$. Two examples are depicted for $L_j = 5 \times 10^{51} \text{ erg s}^{-1}$ (left panel) and $L_j = 10^{50} \text{ erg s}^{-1}$ (right panel). Each snapshot has been rotated by $\pi/2$, where $t = 2, 2.5, 4.5, 5.5 \text{ s}$ (left panel) and $t = 2, 4, 6, 8 \text{ s}$ (right panel). Plotted are the logarithmic density contours $[\rho_{\min}, \rho_{\max}] = [2 \times 10^{-5}, 7.0]$ in g cm^{-3} as well as corresponding $3 \times 10^{10} \text{ cm}$ scale bar.

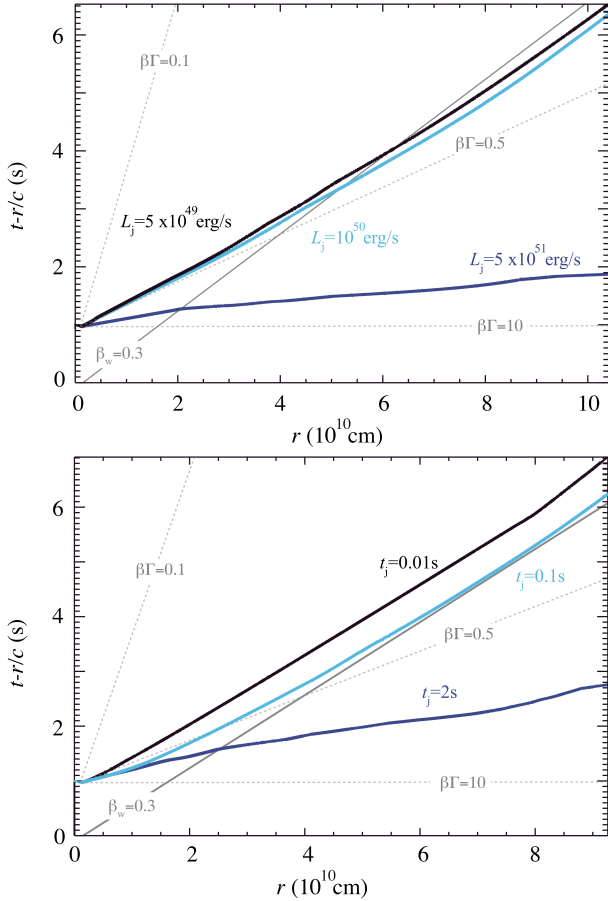


FIG. 5.— Space time diagram in source frame coordinates of a relativistic jet propagating through a wind medium with $\dot{M}_w = 10^{-3} M_\odot \text{ s}^{-1}$, $t_w = 1 \text{ s}$ and $\beta_w = 1/3$. The axes are r versus $t - r/c$, where t is time measured in the source frame and $t = 0$ denotes when the wind starts. Light rays in this diagram are horizontal lines. The jet with $\theta_j = 10^\circ$ and $\Gamma_j = 10$ is injected at $t = t_w$ and is assumed to continue, with a quasi-steady luminosity L_j , for a time t_j . The effects of altering L_j for a fixed $t_j = 1 \text{ s}$ are shown in the *top* panel while the consequences of varying t_j for a fixed $L_j = 10^{51} \text{ erg/s}$ are depicted in the *bottom* panel. Choked jets have $\beta_j < \beta_w$ while jets with $\beta_j \Gamma_j < 0.5$ are able to break free from the wind but they do so sub-relativistically. In both instances a sGRB will not be triggered.

occurs when

$$L_j \gg 5.94 \times 10^{51} \left(\frac{\dot{M}_w}{10^{-3} M_\odot/\text{s}} \right) \text{ erg/s.} \quad (8)$$

The dependence of the jet propagation behavior on L_j/\dot{M}_w is summarized in Fig. 2.

3. NUMERICAL SIMULATIONS

Here we carry out a set of axisymmetric, special relativistic hydrodynamics (SRHD) simulations of the propagation of a jet produced in binary neutron star mergers and its interaction with the previously spouted neutrino-driven wind. The simulations employ the *Mezcal* SRHD adaptive mesh refinement code, a parallel, shock capturing code routinely used to simulate the propagation of relativistic jets (e.g. De Colle et al. 2012b,c). A detailed description of the code and tests of the SRHD implementation are presented in De Colle et al. (2012a). Common to all simulations is the injection of a steady, spherically

symmetric wind for a time period t_w . Immediately after t_w , the jet is injected and the wind power is assumed to decrease with time as $t^{-5/3}$. For simplicity, we consider the relativistic jet to be uniform with sharp edges and an initial half-opening angle θ_j . As a first example, we follow the dynamics of a standard sGRB jet expanding through a neutrino-driven wind that was steadily ejected over $t_w = 1 \text{ s}$ before the merger remnant's collapse and the subsequent formation of the black hole. The properties of the neutrino-driven wind have been chosen to roughly match those envisioned by Dessart et al. (2009) for a hot, differentially rotating merger remnant. Detailed hydrodynamic simulations of the expansion of a relativistic jet in such a wind medium are presented in Fig. 3, where the density profiles of the advancing jet at various times in its evolution are plotted. As the sGRB jet makes its way through the dense wind, its rate of advance is slowed down and both the shocked jet and shocked wind material advance with a jet head Lorentz factor $\Gamma_h \ll \Gamma_j$. The excess energy must then not collect near the working surface but be accumulated within a cocoon engulfing the jet. The jet would be expected to escape from the wind region as long as $t_j > t_{j,b}$ (equation 6). Fig. 3 depicts the two types of behavior expected for a steady sGRB jet expanding in a dense wind with $\beta_h > \beta_w$. For $t_j > t_{j,b}$, the jet comes out from the edge of the wind at $r_w = t_b \beta_w c$ into an exponentially decreasing atmosphere and into the rarefied ISM beyond it. The jet will then attain a bulk Lorentz factor Γ_j soon after its emergence and could lead to a successful sGRB. For $t_j < t_{j,b}$, the jet starts to drastically decelerate before it reaches the edge of the wind and is unable to break free. An accompanying sGRB will not be present in this case. Some conditions increase the likelihood of a successful break-through of the jet. At a fixed jet luminosity, the risk of stalling is lower when the lifetime of the post-merger remnant is short or when mass ablation is less efficient. The risk of choking can be also mitigated to a lesser extent by increasing the jet power. A similar calculation to that depicted in Fig. 3 can be generated for jets with varying luminosities but similar durations (Fig. 4). For a relatively low luminosity, the rate of advance of the jet is slowed down drastically and, as a result, the jet is unable to break free (i.e. $t_j < t_{j,b}$). Only when the luminosity is greatly increased would the jet be able to successfully emerge from the wind and subsequently give rise to a sGRB. Note that this is akin to the situation present in long GRBs from collapsars, where the relativistic outflow has to drill through the stellar envelope, with possible observational signatures related to the distribution of angular momentum within the star (e.g. López-Cámara et al. 2010).

It is evident from the above discussion that the environment of a binary neutron star merger at the time of black hole formation is complex and that the properties of the neutrino-driven wind have a decisive effect on jet propagation. The triggering of a sGRB will depend sensitively on the jet power and the time over which the jet is injected. Fig. 5 shows the schematic world-lines of jets with varying properties propagating through the same wind environment. The importance of the longevity of the jet (relative to t_w) and the significance of the jet power are clearly illustrated.

4. DISCUSSION

The rate of neutrino-driven mass loss (equation 1) emanating from the merger remnant, as argued in Sections 2 and 3, has significant repercussions on the appearance of a relativistic jet propagating through it. But the requirements for successful break-through are most sensitive to the duration of the neutrino-driven wind phase (t_w), which in turn depends on the stability of the resulting hot, differentially rotating post-merger configuration. If collapse to a black hole and the ensuing jet production is significantly delayed (i.e. $t_w > 0.1$ s), the majority of jets will not be able to break free from the wind during the typical duration of a sGRB. On the contrary, if collapse occurs more promptly (i.e. $t_w \ll 0.1$ s), the successful break-through of the jet would take place swiftly enough to allow for the production of a typical sGRB.

The observed duration distribution of sGRBs can thus be used to constrain the longevity of the post-merger remnant, which is currently under debate. In systems where a stable remnant is formed (the magnetar model; e.g. Metzger et al. 2008b), jet formation can not be notably delayed (≤ 100 ms) from the onset of the neutrino-driven wind. Otherwise, a choked jet would result without exception. This is because in stable (hyper-massive) neutron stars, the neutrino-driven wind is expected to continue for at least a diffusion timescale, which is commensurate with the duration of the longest lasting sGRB. Effective sGRB production under such circumstances would not only be afflicted by baryon contamination (equation 2) and wind confinement (equation 7) but also by the time delay between the onset of neutrino-driven mass ablation and jet formation. Whatever one's view of the relative merits of the magnetar and the black hole plus debris disk models in producing ultra-relativistic outflows, it is clear that the presence of a long lived, dense wind, a common feature in the magnetar model, severely hinders the successful production of a sGRB.

The shocks responsible for producing the γ -rays must surface after the jet has broken free from the neutrino-driven wind. For a large subset of compact merger progenitors, with the exception of black hole neutron star mergers, a hyper-massive remnant will be formed. A neutrino-driven wind will thus persist to obstruct the progress of the jet. The cocoon would be able to collimate the jet provided that $\tilde{L} < \theta_j^{-4/3}$ (Bromberg et al. 2011). In the simplest case considered here of a wind whose properties do not vary over its lifetime, the jet's head velocity is constant and the cocoon is unable to compensate for the jet's expansion (Figures 3 and 4). Collimation is seen to increase with decreasing k for $k \leq 2$ where $\rho_w \propto r^{-k}$. While writing this paper we became aware of a recent preprint (Nagakura et al. 2014), in which the interaction of a jet with the previously dynamically ejected material (which is independent of the neutrino-driven wind we consider here) in a binary merger (Hotokezaka et al. 2013b) is used to argue as an effective mechanism for the collimation of a sGRB jet.

The energy supplied by the jet exceeds that imparted to the swept-up wind material by a factor $\beta_h/\beta_j < 1$. The excess energy must then not gather near the working surface but be deposited within a cocoon surrounding the jet (Figures 3 and 4). Unless there is violent mixing of baryons from the wind, the build-up of energy to baryon-

rest-mass in the cocoon will be given approximately by $\approx \Gamma_h$. As soon as the jet reaches the edge of the wind, r_w , the cocoon material would itself be able to break-out and expand through the wind along the direction of least resistance, which is likely to be along the jet's axis. Beyond r_w , the external pressure drops steeply, and the cocoon material will expand freely with $\Gamma_c \propto r/r_w$ (Ramirez-Ruiz et al. 2002). If its unhampered transverse expansion starts just outside r_w , where the Lorentz factor of the cocoon material is only a few, then it will spread over a wide angle.

In the case of a successful break-through of the relativistic jet, the outflowing cocoon could result in potentially interesting and observable phenomenon (Ramirez-Ruiz et al. 2002; Thompson et al. 2007; Morsony et al. 2007). The relativistic material that accumulated in the cocoon could have an energy comparable to that of the jet when $t_j \gtrsim t_{j,b}$. Not only would a typical sGRB be detectable, followed by a standard afterglow, but also there could be additional emission before and after the main event when the cocoon material becomes transparent and when it decelerates. While the main afterglow radiation will be produced by the slowing down of the jet as in the usual case, prompt X-ray emission at early stages could be caused by the deceleration of the cocoon blast wave, which is expected to be less energetic. This could resemble the so called *extended emission* in sGRBs (Norris & Bonnell 2006), in particular if it is slowly varying. There could also be precursor signatures (Ramirez-Ruiz & Merloni 2001; Troja et al. 2010) which are not associated with internal dissipation in the jet, but with the dynamics of the cocoon fireball. The γ -ray signal emerging from the cocoon fireball as it becomes transparent will most likely appear as a transient signal before the beginning of the main burst (Ramirez-Ruiz et al. 2002; Suzuki & Shigeyama 2013), where the observed variability time scale would be related to the typical size of the shocked plasma region containing the photon field: $\Delta \approx r_w$ for $r/\Gamma_c^2 < \Delta$. The detection of these prompt signatures would be a test of the neutron star binary merger model and the precise measurement of the time delay between emissions may help constrain the duration and properties of the neutrino driven wind phase.

If we were to venture a general classification scheme for GRBs, on the hypothesis that the central engine involves a black hole formed in double neutron star mergers, we would obviously expect the disk and black hole mass (Lee et al. 2005b; Oechslin & Janka 2006; Giacomazzo et al. 2013), the angular momentum of the black hole and the orientation relative to our line of sight to be essential parameters. It is then necessary, within such a model, to identify sGRBs with merging systems for which black hole formation occurs promptly (≤ 100 ms) as any moderate delay at the hyper-massive neutron star stage would result in a choked jet.

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